Prospects for Sterile Neutrino Searches in MiniBooNE

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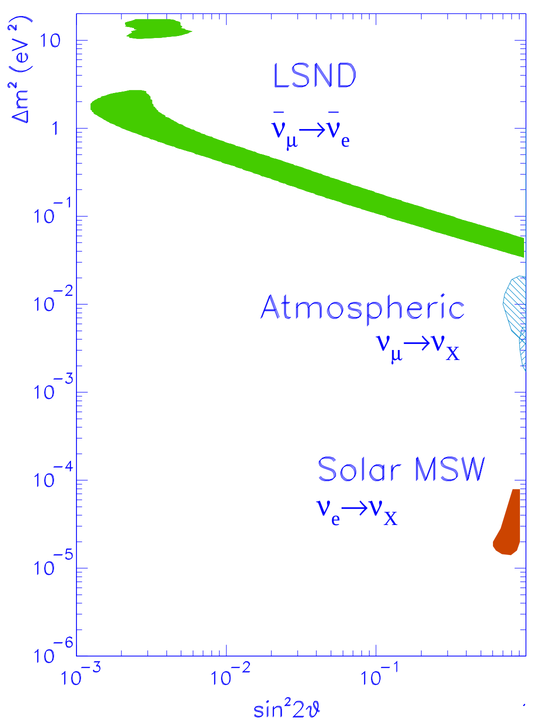
Outline

- Present experimental constraints on sterile neutrino models
- Sensitivity to sterile neutrinos in MiniBooNE
- Neutrino flux and cross-sections, and their importance for the MiniBooNE ν_μ disappearance measurement

Beyond minimal extensions of the SM

- Minimally extended SM: three massive neutrinos
- There are three experimental hints pointing toward neutrino oscillations:



- Two-neutrino oscillation approximation:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}, \; \Delta m^2 = m_2^2 - m_1^2$$

- Oscillation probabilities:

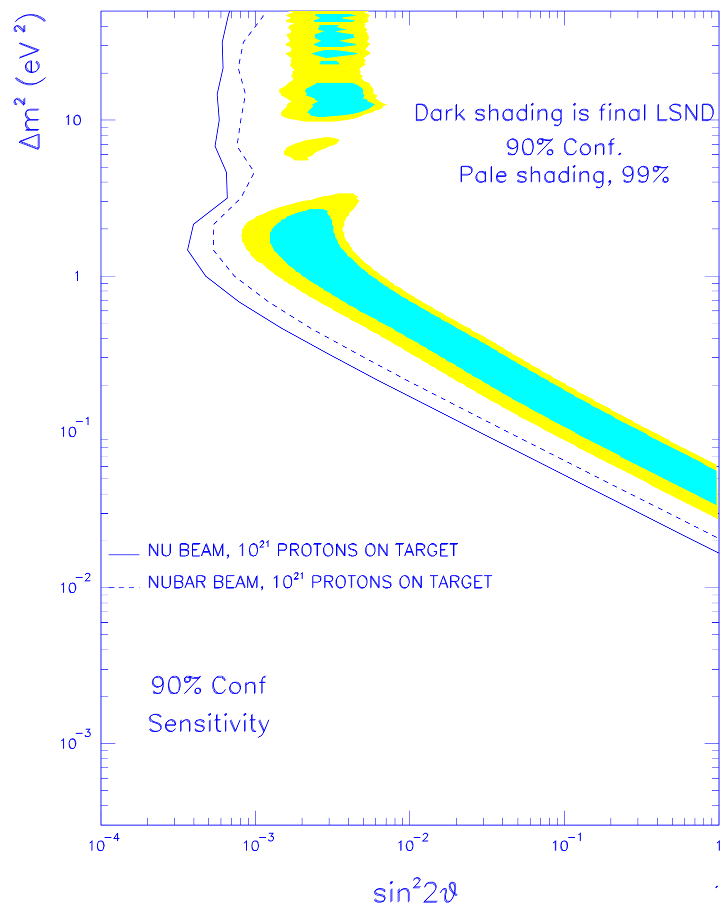
$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2(1.27 \Delta m^2 L/E), \; \alpha \neq \beta$$

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2(1.27 \Delta m^2 L/E)$$

- $\Delta m^2_{sol} + \Delta m^2_{atm} \neq \Delta m^2_{LSND} \Rightarrow$ need more than three massive neutrinos?

Is LSND due to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations? MiniBooNE will tell

- The LSND evidence: $\langle P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)\rangle = (0.264 \pm 0.045 \pm 0.067)\%$
- MiniBooNE will address in a definite and independent way the LSND evidence for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations



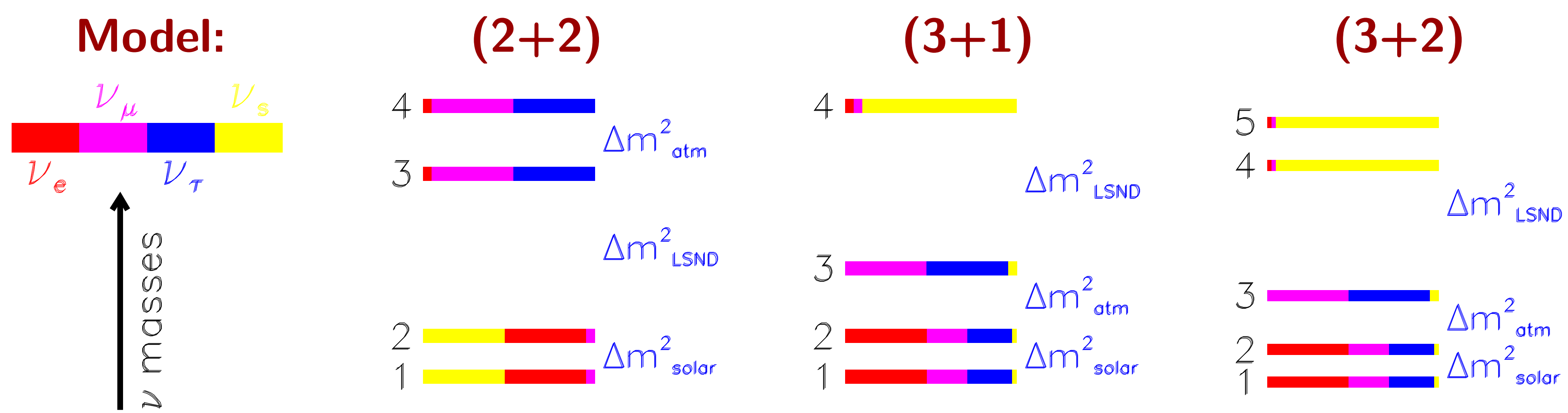
- definite: same L_ν/E_ν ratio as for LSND and enough statistics to cover the LSND region at the 5σ level
- independent: $E_\nu = 0.3 - 1.5$ GeV and $L_\nu = 540$ m are both a factor of 10 larger than LSND, resulting in very different backgrounds to the oscillation search and systematics for the ν flux and particle ID

Sterile neutrino models: a wide range of possibilities. . .

- Can solar, atmospheric, and LSND be explained by introducing one or more neutrinos with no standard weak couplings ("sterile neutrinos")?

- Noninteracting particles can be hard to find experimentally, but not theoretically. . . most theories explaining the origin of neutrino masses require sterile neutrinos!

- Possible neutrino mass and mixing scenarios (colored boxes indicate weak flavor content of mass eigenstates):



Constraints on (3+1) and (3+2) models from SBL experiments

- General oscillation formula depends on several neutrino masses m_i and elements $U_{\alpha i}$ of the mixing matrix relating flavor to mass eigenstates:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{j>i}^{n}\sum_{i}^{n} U_{\alpha j}U_{\beta j}U_{\alpha i}U_{\beta i}\sin^2[1.27L(m_j^2 - m_i^2)/E]$$

- (3+1), (3+2): can consider constraints from short-baseline experiments only
  - (3+1): $P(\nu_\mu \rightarrow \nu_e)$ depends only upon $m_4, U_{e4}, U_{\mu 4}$
  - (3+2): $P(\nu_\mu \rightarrow \nu_e)$ depends only upon $m_4, U_{e4}, U_{\mu 4}, m_5, U_{e5}, U_{\mu 5}$

- Method: perform a combined χ^2 analysis of the "Null Short- BaseLine" experiments Bugey and CHOOZ ($\bar{\nu}_e \rightarrow \bar{\nu}_x$), CCFR and CDHS ($\nu_\mu \rightarrow \nu_x$), KARMEN ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$), to derive upper limits on the LSND oscillation probability

$p_{LSND} \equiv \langle P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)\rangle_{LSND}$: $\bar{\nu} \rightarrow \bar{\nu}_e$ probability averaged over LSND L/E distribution

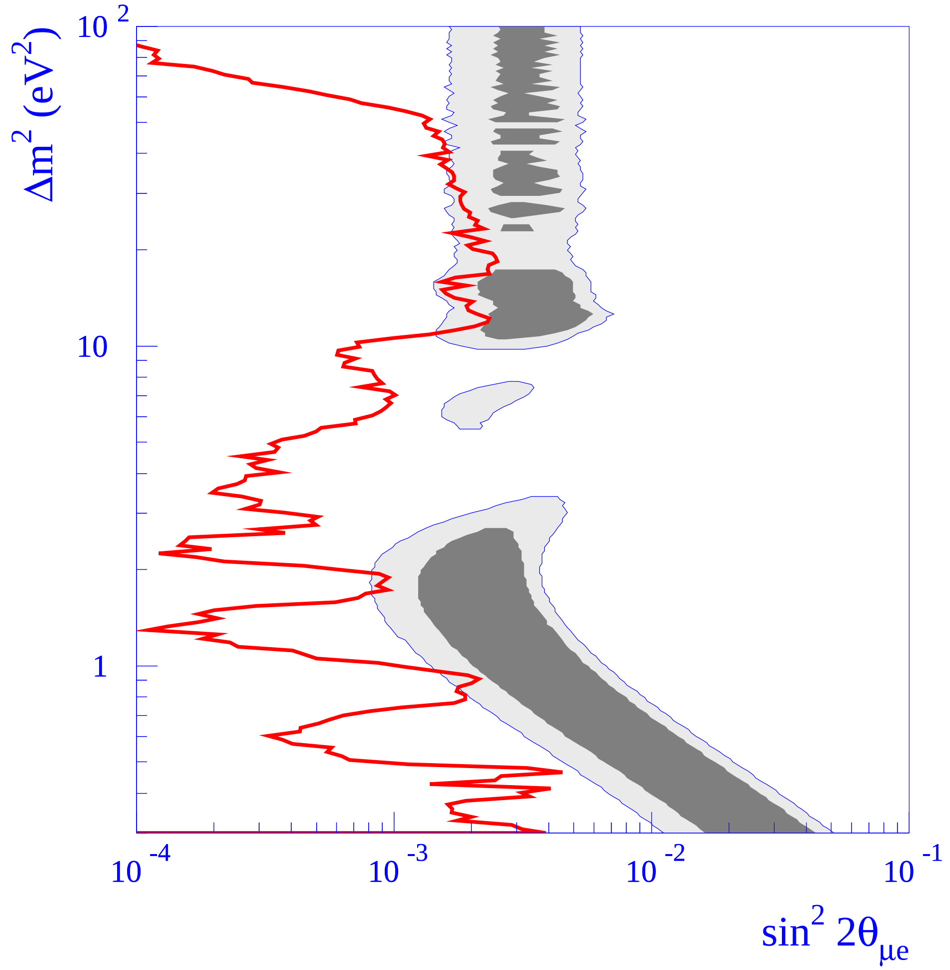
$\Rightarrow$ is this NSBL upper limit consistent with the nonzero LSND result?

The (3+1) case

Two-neutrino approximation is valid for (3+1) models

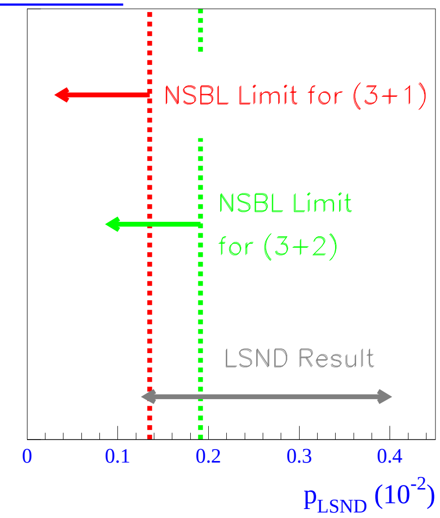
$\Rightarrow$ In $(\sin^2 2\theta_{\mu e}, \Delta m^2)$ space, the region to the right of the curve is EXCLUDED at 90% CL by NSBL experiments

Some Δm^2 "islands" are allowed



The (3+2) case

Limits on the LSND oscillation probability (90% CL)



$$p_{LSND} \equiv \langle P(\bar{\nu}_\mu \to \bar{\nu}_e) \rangle_{LSND}$$

$\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ probability averaged over LSND L/E

NSBL 90% upper limits for (3+2) models are less stringent than for (3+1) models by $\simeq$ 40%

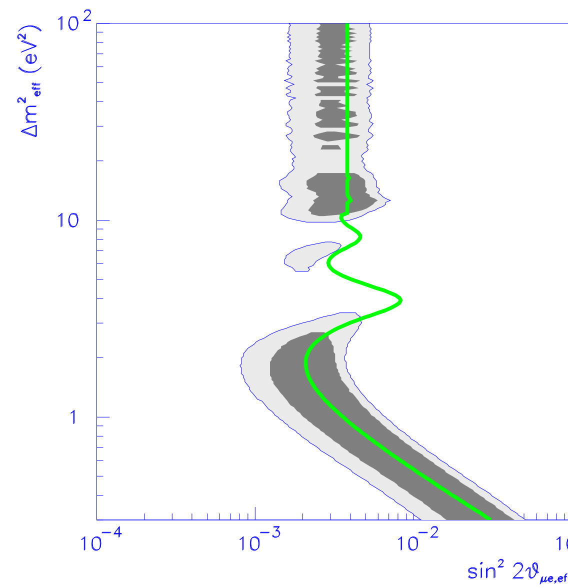
$\Rightarrow$ (3+2) models to be preferred to (3+1)?

Limits on "2ν mixing" (90% CL)

2ν approximation is not valid for (3+2), since there are three Δm^2: m_4^2, m_5^2, $m_5^2 - m_4^2$.

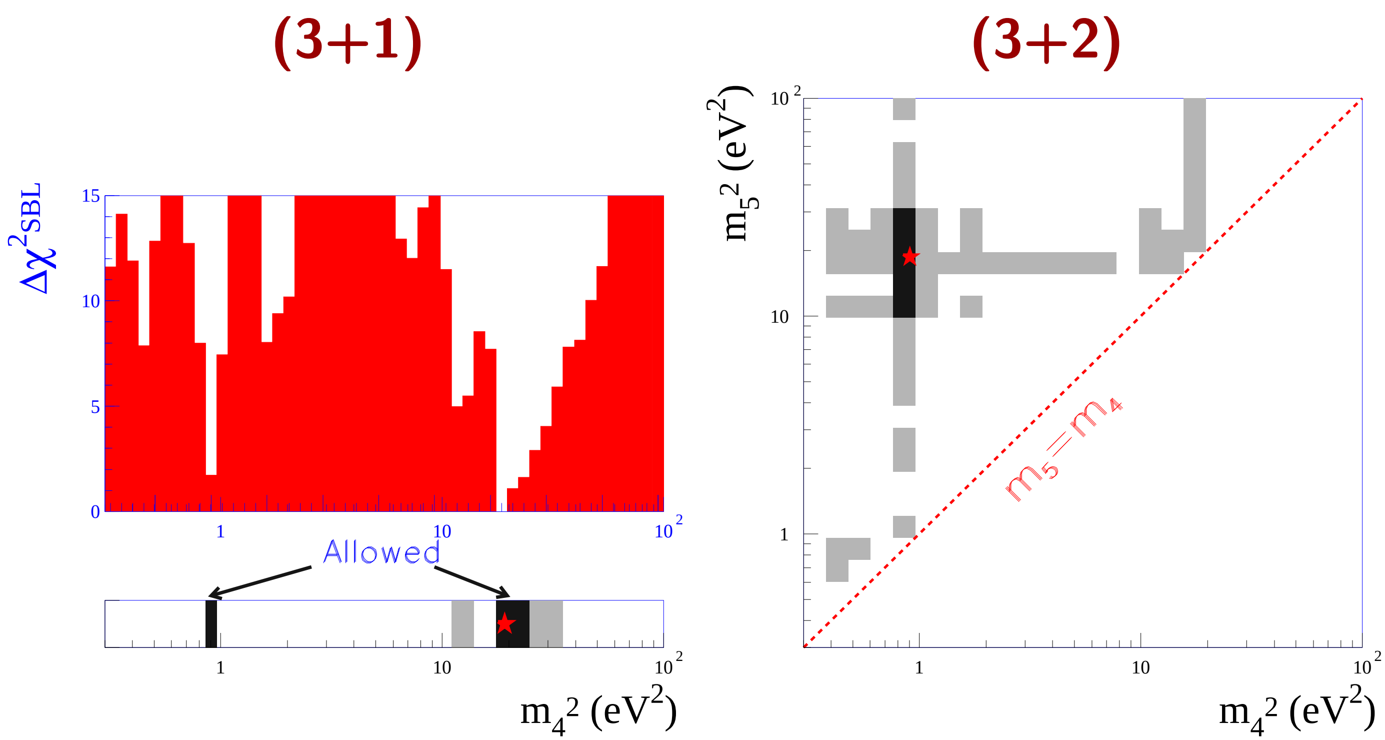
Define "effective" 2ν mixing angle $\theta_{\mu e}$ and Δm^2:

$$\sin^2 2\theta_{\mu e,eff} \langle \sin^2(1.27 \Delta m^2_{eff} L/E) \rangle_{LSND} \equiv p_{LSND}$$



Preferred values of neutrino masses in (3+1) and (3+2) models

- A joint analysis of NSBL and LSND data gives the following allowed regions (grey is 90% CL, black is 99% CL):



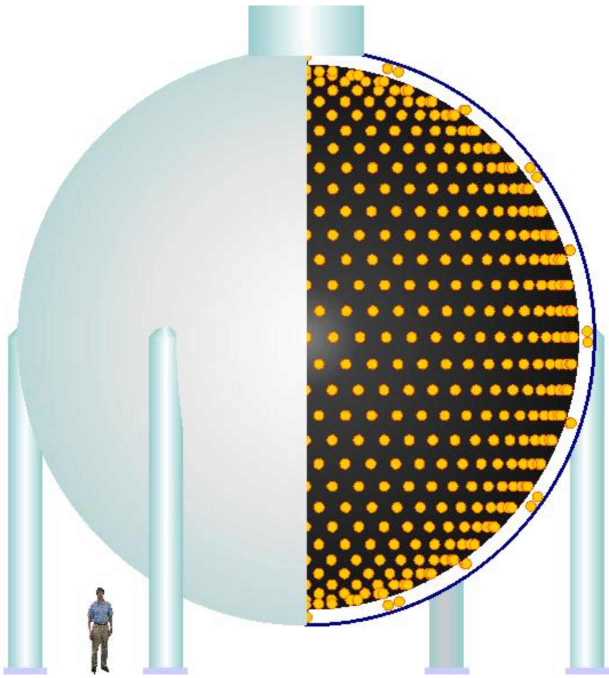
- A combined analysis gives much better guidance than LSND alone on what Δm^2 might be responsible for the LSND signal

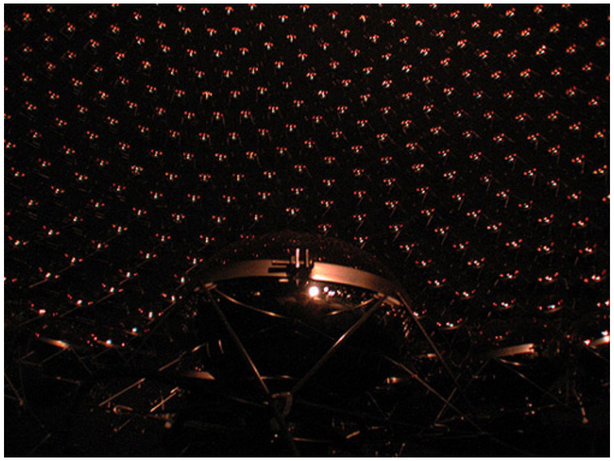
MiniBooNE

- 12 m in diameter sphere filled with 800 tons of mineral oil

- A sphere-within-a-sphere:
  - Light tight inner signal region is lined with 1280 PMTs
    10% coverage
  - Outer spherical shell serves as veto region (240 PMTs)

- Neutrino interactions in the oil produce:
  - Prompt and ring-distributed Cherenkov light
  - Late and isotropically-distributed scintillation light





The BooNE Collaboration

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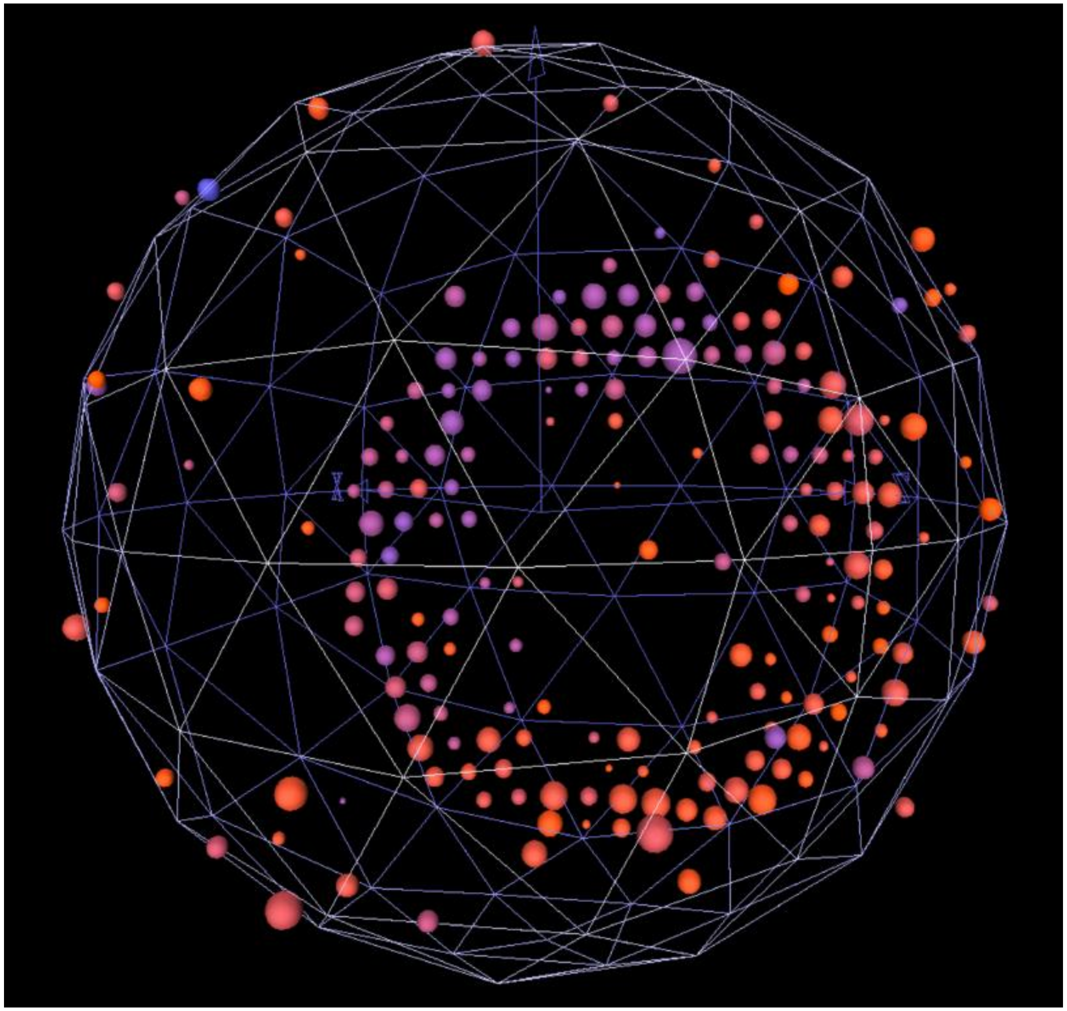
Typical muon candidate event



MiniBooNE physics potential

- MiniBooNE result on $\nu_\mu \longrightarrow \nu_e$ search expected by 2005
- Between now and 2005. . .
  - results on ν_μ disappearance
  - searches for exotic particles
  - supernova watch
  - cross-section measurements
- Neutrino models explaining LSND can give a measurable ν_μ deficit in MiniBooNE:

Model	Is a MiniBooNE Disappearance Sensitive?
(3+1)	yes
(3+2)	yes
(2+2)	no?
CPTV	yes (in $\bar{\nu}_\mu$ running)

ν_μ disappearance in (3+1): how large can it be?

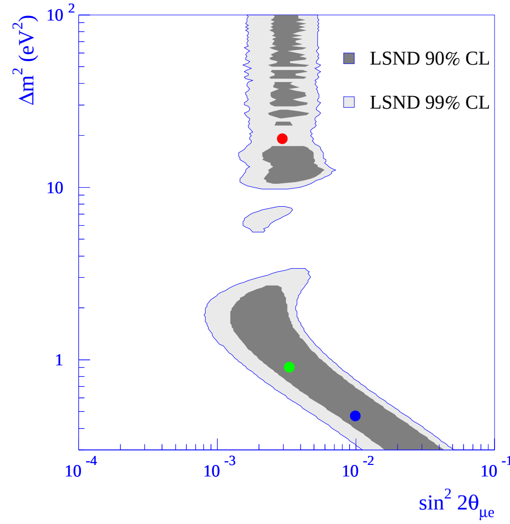
Pick as example three viable models, from joint NSBL+LSND analysis:

$m_4^2 = 19\ eV^2,\ U_{e4} = 0.12,\ U_{\mu 4} = 0.23$

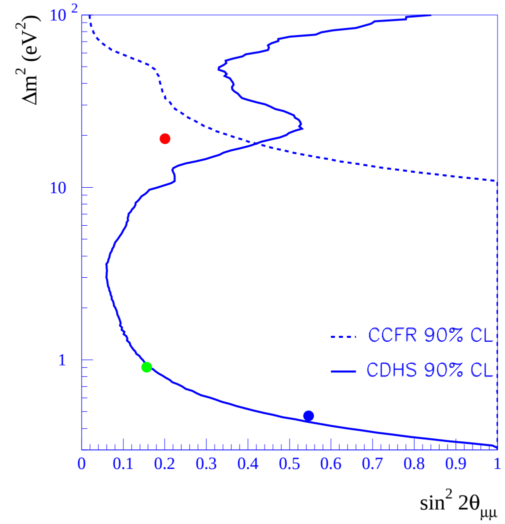
$m_4^2 = 0.91\ eV^2,\ U_{e4} = 0.14,\ U_{\mu 4} = 0.20$

$m_4^2 = 0.47\ eV^2,\ U_{e4} = 0.12,\ U_{\mu 4} = 0.40$

$\nu_\mu \longrightarrow \nu_e$ space:

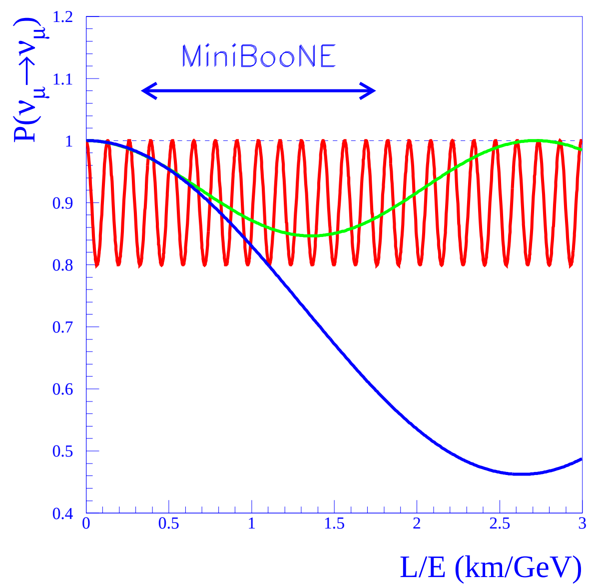


$\nu_\mu \longrightarrow \nu_x$ space:



MiniBooNE can see a large ν_μ deficit

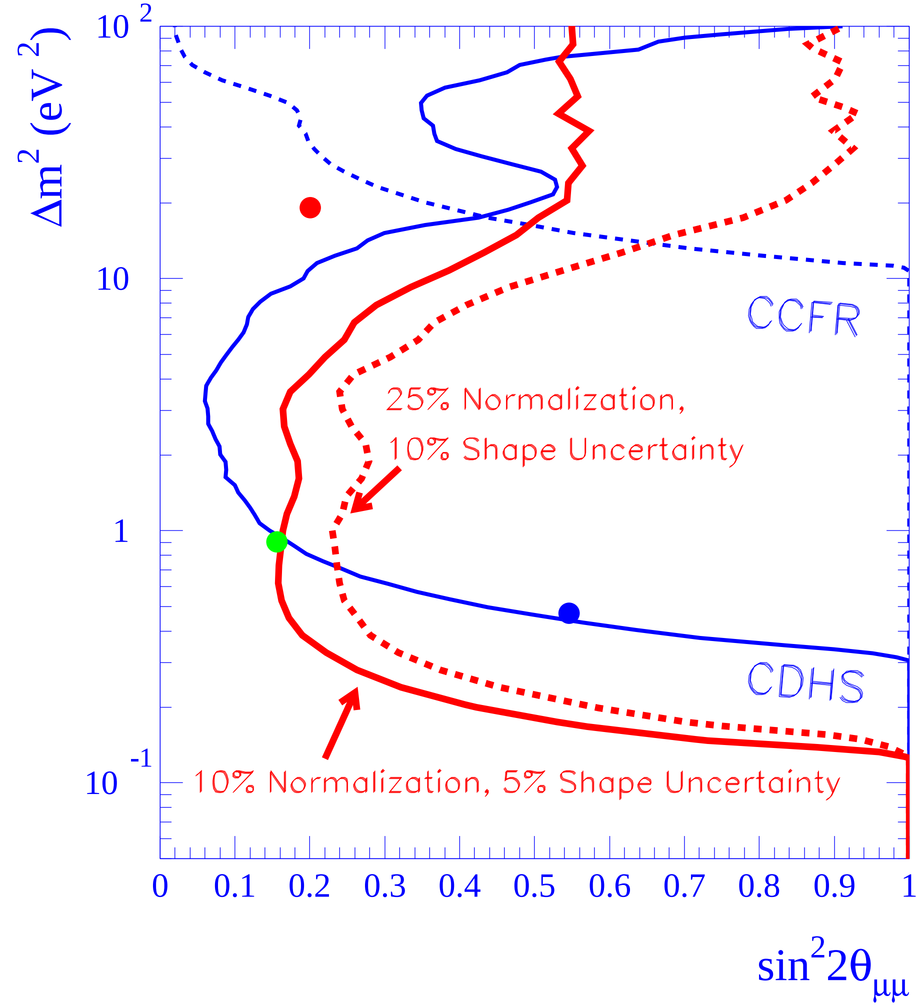
Energy shape information can significantly improve the MiniBooNE sensitivity for:
few $0.1 \leq \Delta m^2 \leq$ few eV^2



ν_μ disappearance sensitivity in MiniBooNE

Expected MiniBooNE 90% CL sensitivity by the end of the year should lie somewhere between the solid and the dashed red line…

Dots are predictions for some viable (3+1) models

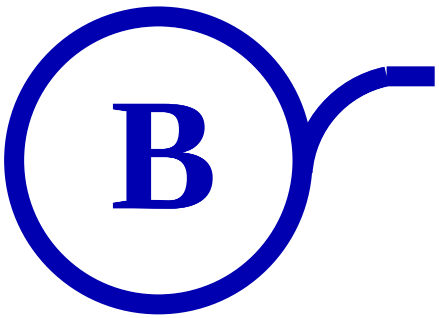


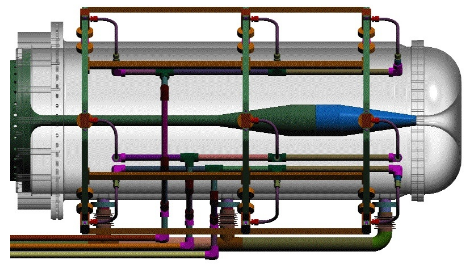
- MiniBooNE reach at low Δm^2 should extend significantly beyond present limits. This is a very interesting neutrino mass region!

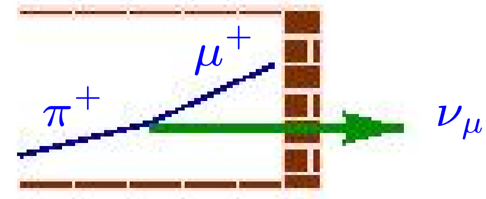
ν_μ disappearance: limiting experimental factors

- The MiniBooNE ν_μ measurement will be systematics-dominated
- Systematics affecting the rate and energy distribution:
  - Number of beam protons
  - ν_μ flux
  - ν_μ cross-sections
  - Event reconstruction
  - Energy resolution/calibration
  - Event selection
- A two-detector experiment (BooNE?) can
  - push the sensitivity curve "to the left": by taking far-to-near ν_μ event rate ratios, some systematic uncertainties cancel
  - push the sensitivity curve "down": by placing the 2nd detector downstream of the 1st, low Δm^2 reach can be further extended
- Main uncertainties: ν_μ flux and cross-section

The BooNE Beam







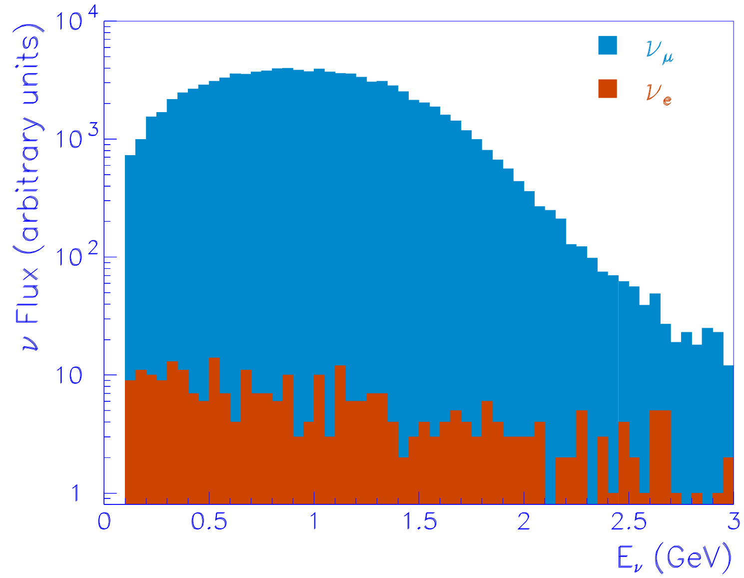
Primary Beam:
high-intensity 8 GeV proton source from FNAL Booster.
MiniBooNE requires 10^{21} protons on target $\Leftrightarrow$ 2 years of running

Secondary Beam:
protons strike a 71 cm beryllium target, producing secondary $\pi^{\pm}$'s, $K^{\pm}$'s.
Magnetic focusing of secondary beam from horn surrounding the target

Neutrino Beam:
$\pi^+ \longrightarrow \mu^+ \, \nu_\mu$ in the 25/50 m decay channel.
After absorber, almost pure ν_μ beam pointing towards the detector

Neutrino flux in MiniBoONE

- ν_μ flux peaks at $\simeq 1$ GeV
- Flux uncertainty is due to the π^+ production uncertainty in p-Be interactions

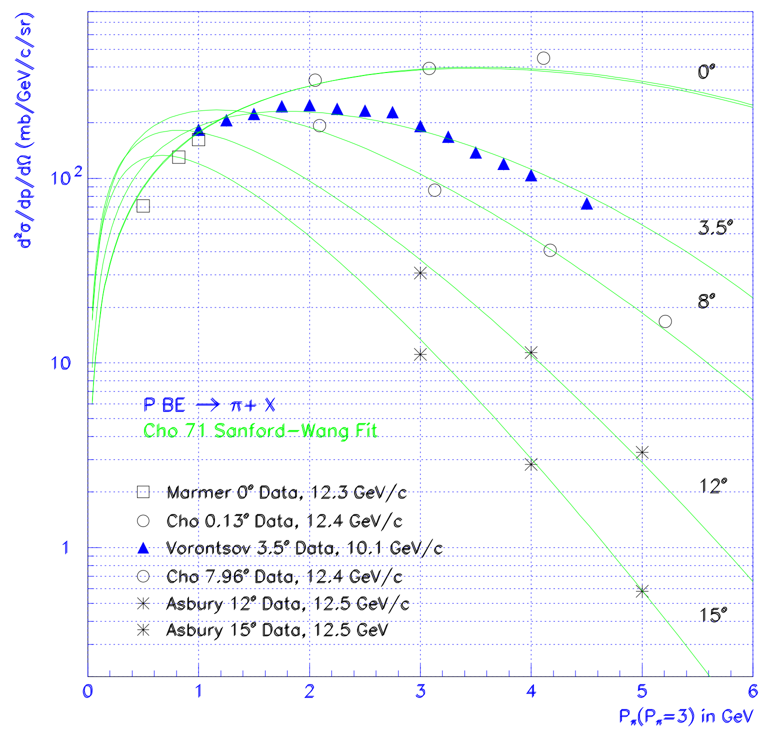


- To gain a better understanding of the flux:
  - combined analysis of existing π production data in p-Be
    $\Rightarrow$ "K2K-style" global parametrization of $d^2\sigma/dp\, d\cos\theta$ for $p + Be \rightarrow \pi^+ + X$
  - collaboration with BNL E910 experiment to analyze more recent data on thin Be targets
  - collaboration with HARP experiment at CERN
    $\Rightarrow$ data taken last summer with replica of thick Be target used in MiniBooNE; data analysis is ongoing
  - GEANT4-based simulation of the flux interfaced to all this wealth of physics information

Flux 1: combined analysis of existing $p + Be \rightarrow \pi^+ + X$ data

- MiniBooNE needs: $p_b = 8.9$ GeV/c, $p_\pi = 0.5$ - 4 GeV/c, $\theta_\pi = 0$ - 15 deg
- "Sanford-Wang" parametrization fits data reasonably well (10-15% level):

Experiment	θ_π *(deg)*	p_b *(GeV/c)*	p_π *(GeV/c)*	*Error*
Allaby 70	0 - 5	19.1	6 - 18	15 - 20%
Asbury 68	12, 15	12.5	3 - 5	15%
Cho 71	0 - 11	12.4	2 - 6	10 - 15%
Dekkers 64	0, 5	18.8	2 - 12	10%
E910 2001	15, 31.8	12.3, 17.5	0.1 - 1.2	5 - 10%
Marmer 71	0, 3, 5	12.3	0.5 - 2.5	15%
Papp 75	12.5	1.753 - 5.0	0.5 - 3.5	10%
Vorontsov 88	3.5	10.1	1 - 4.5	25%

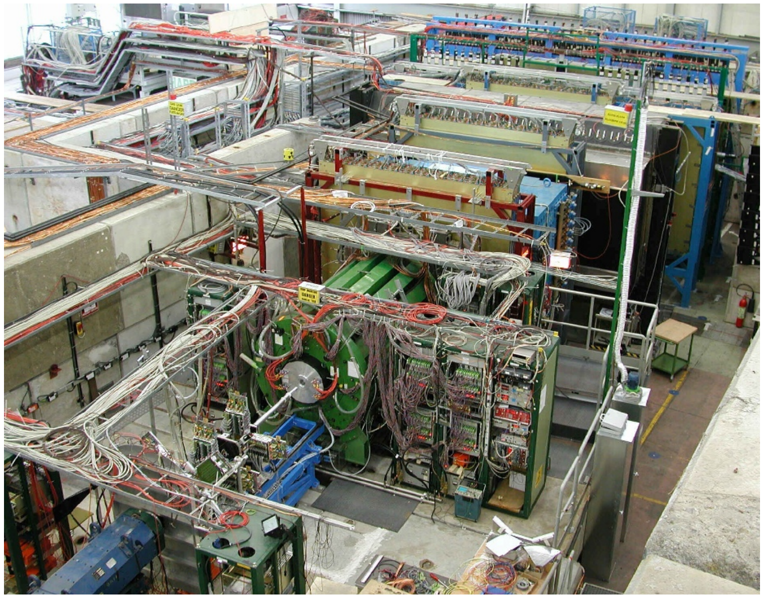


(analysis by Jocelyn Monroe, Columbia U.)

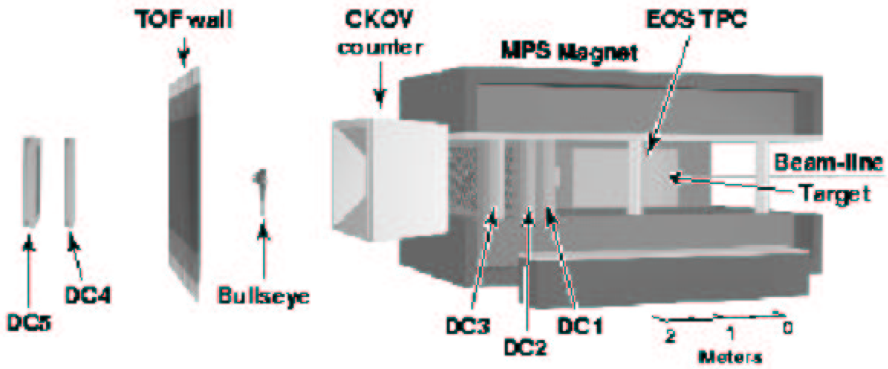
Flux 2: HARP and BNL E910

- Current generation experiments, with better statistics and particle ID, 4π coverage, wider choice of beam momenta and targets

HARP



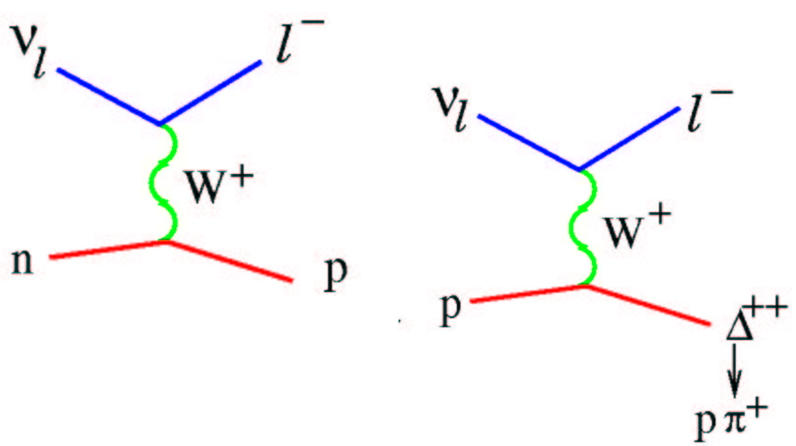
BNL E910

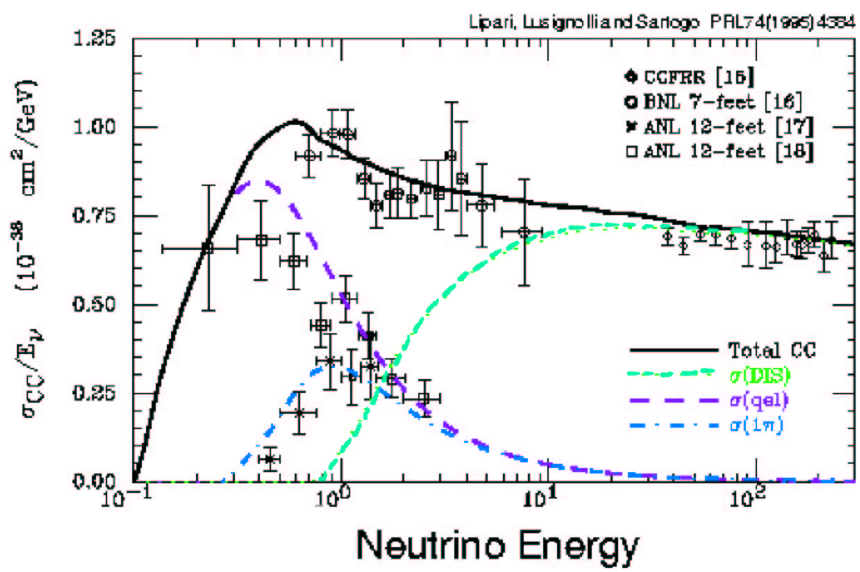


- Goal: reduce uncertainty in π-production data to the few % level
- HARP should allow us to understand π^+ reinteractions in Be as well (thin/thick target comparisons)

Neutrino cross-sections in the ~ 1 GeV range

- For a good review: Sam Zeller, "Low Energy Neutrino Interactions", U1.004
- Dominant processes at $1 \simeq$ GeV are neutrino-nucleon Quasi-Elastic scattering and resonant π production:



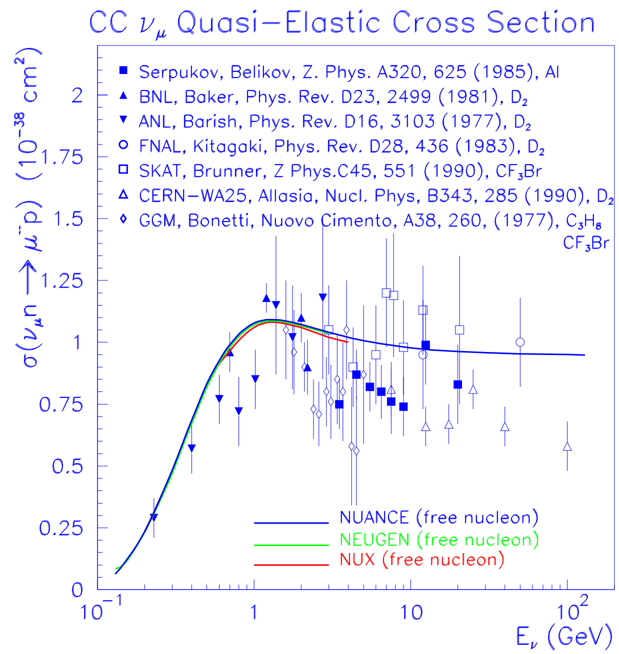


- Not very well understood:
  - Not much data
  - Nuclear effects play an important role
  - Transition region: inelastic channels start to contribute

Quasi-Elastic cross-section and ν_μ disappearance

The best known process is the QE interaction

$\Rightarrow$ select a "QE-like" data sample only for MiniBooNE ν_μ disappearance?



- Collaborative effort to improve the cross-section knowledge is ongoing. Two examples:
  - use e^--nucleus scattering data to understand nuclear effects
  - reanalyze 20 yr-old data with updated free nucleon form factors (see H. Budd, A. Bodek, P13.011)

Summary

- Phenomenologists like sterile neutrinos to explain LSND...
  and theorists like them too!

- Combining LSND with other oscillation results provides hints where to look

- How to find sterile neutrinos? Disappearance measurements

- Disappearance can be large!

- MiniBooNE ν_μ disappearance result will extend beyond our current sensitivity reach

- 50k ν_μ event candidates are on tape already, and MiniBooNE should have a competitive ν_μ disappearance measurement by 2003

- Conclusive test of the LSND evidence for oscillations in 2005, with the MiniBooNE $\nu_\mu \longrightarrow \nu_e$ result